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CW diode-pumped optical parametric oscillator in bulk periodically poled $LiNbO_3$

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Indexing terms: Lithium niobate, Parametric oscillators

The authors report a 1.96μm doubly resonant optical parametric oscillator using bulk periodically poled $LiNbO_3$ directly pumped by a commercial 980nm CW diode laser.

An optical parametric oscillator (OPO) directly pumped by a diode laser is potentially a compact and efficient source of tunable radiation. Implementations using available nonlinear optical materials have been hampered because the gain and phasematching placed difficult constraints on the wavelength and power requirements of the pump laser [1]. With the engineerable phasematching and high gain properties available through quasi-phasematching (QPM), we recently demonstrated an OPO directly pumped by a commercial CW diode laser [2].

The nonlinear optical material was periodically poled $LiNbO_3$ (PPLN) fabricated using the electric field poling technique reported in [3, 4]. The low loss, high gain, and noncritical phasematching of this material make it desirable for low peak power OPOs, particularly with CW diode laser pumping. The pieces for the work reported here were 0.5mm thick with a 9.3mm interaction length. The domain period for quasi-phasematching was 28.5μm, designed for degenerate operation at 88°C [5]. The polished end faces of the PPLN were AR coated for the signal/idler pair near degeneracy at 1.96μm. The actual AR coating came out slightly short centred at 1.84μm, and the total single pass power loss through the crystal was ~0.8% at 1.96μm.

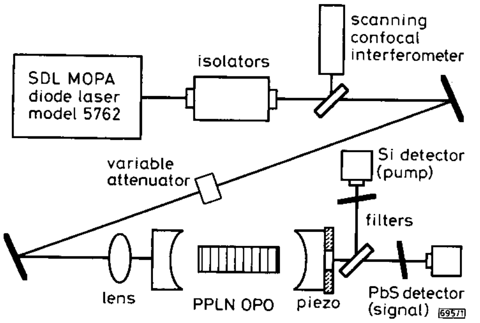

Fig. 1 *Experimental setup for diode-pumped OPO in bulk PPLN*

OPO cavity mirrors have 10mm radius of curvature, input coupler is high reflector and output coupler is either 99.3 or 99.7% reflector at signal/idler wavelengths

The experimental setup of the diode-pumped OPO is shown in Fig. 1. The pump was a 977.6nm master oscillator/power amplifier (MOPA) diode laser from SDL, Inc. (model 5762), operating at 500mW. We used a scanning confocal interferometer with a resolution of ~25MHz to verify single frequency operation of the diode laser. The laser was susceptible to even small amounts of feedback; –60dB of isolation was required for stable operation. The doubly resonant OPO resonator was a linear cavity with 10 mm radius of curvature mirrors separated by 22mm. We used a high reflectivity input mirror and output couplers of 0.3 and 0.7% transmission, all centred at 1.96μm. The useful bandwidth of the mirrors was ~200nm, and the pump reflectivity was ~20% for each mirror. The pump beam was focused to a 33μm waist in the cavity with a beam quality of $M^2 = 1.3$. The beam had an ellipticity of 1.2 and astigmatism of 2.5mm in the focus locations in air. The output coupler was mounted on an annular piezoelectric element for cavity length control. The OPO output near 1.96μm was detected with a PbS detector after a filter that blocked the pump beam, and the transmitted pump beam was detected with a Si detector.

The threshold for a doubly resonant OPO (DRO) is given by [6]

$$P_{th} = \frac{a_s a_i n_s n_i c^4 \varepsilon_0 \pi}{4\omega_s \omega_i \omega_p d_Q^2 L \bar{h}_m}$$

where $\bar{h}_m$ is the reduction factor for a focused interaction, L is the crystal interaction length, ω_p, ω_s and ω_i are the pump, signal and idler frequencies, respectively, and n_s, n_i, a_s and a_i are the refractive indices and round trip power losses of the signal and idler, respectively. The nonlinear coefficient for QPM is $d_Q = (2/\pi)d_{33} = 13.2$pm/V, where $d_{33} = 27$pm/V [7], measured for second harmonic generation of 1.064μm, has been adjusted for the interaction here with a constant Miller delta. The factor of $2/\pi$ accounts for first-order QPM. The round trip power losses were 1.9 and 2.3% for the 0.3 and 0.7% output couplers, respectively. For optimal focusing, $\bar{h}_m = 1.07$; in our case, $\bar{h} \simeq 0.63$. The predicted threshold powers were 52 and 76mW for the 0.3 and 0.7% output couplers, respectively; the measured thresholds were 61 and 98mW. The peak phasematching temperature was 91°C, which agrees with the design calculation.

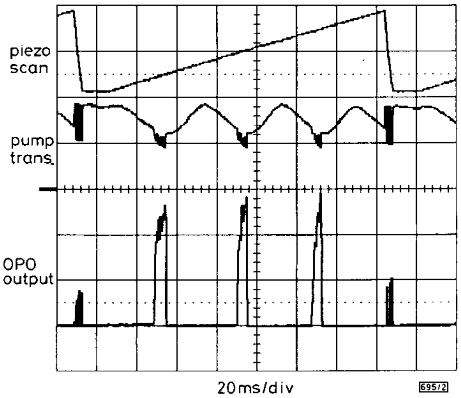

Fig. 2 *Cavity mirror piezo scan voltage, pump transmission with depletion, and ~1.96μm OPO output signals with 0.7% output coupler*

Fig. 2 shows the cavity mirror piezo voltage, pump transmission through the cavity, and the OPO output through the 0.7% output coupler as the cavity length is scanned with the piezo. The fact that the OPO oscillated during the pump transmission minimum indicates that threshold was reached without pump enhancement in the cavity. For 370 mW of pump incident on the cavity mirror, we measured peak output powers of 34 and 64mW for the 0.3 and 0.7% output couplers, respectively. These values were determined by measuring the average power in the output beam and adjusting for the duty factor of the actual OPO operating time over the piezo scan. The conversion efficiencies of 9 and 17% are close to the values observed in pump depletion.

The OPO runs in disjoint regions as a function of the cavity length, owing to the cluster effect that is well-known for DROs. As seen in Fig. 2, the cavity length change corresponding to the cluster spacing is half of the pump wavelength, i.e. 489nm. We monitored the spectral content of the OPO output using a 1 m monochromator. The output spectrum was erratic owing to lack of cavity stabilisation, but the average wavelength showed a clear dependence on the cavity mirror separation, which is plotted in Fig. 3. With mirror translation of 70nm, signal/idler pairs were observed from 1.85 to 2.08μm, which matches the mirror bandwidth. As the cavity length is scanned, the output frequencies follow the cavity resonances until they reach degeneracy. There is a subsequent gap in the OPO output until the cavity length changes enough to bring another cluster within the mirror bandwidths.

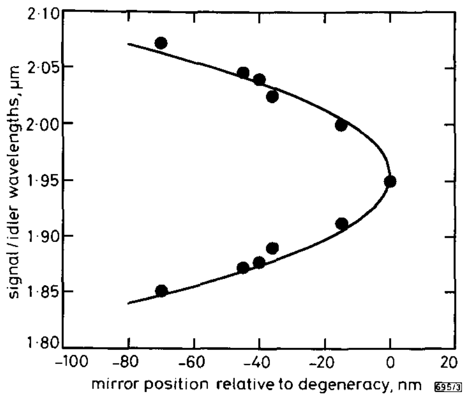

Fig. 3 *Average wavelength of output of CW diode-pumped DRO against cavity mirror separation*

Tuning was limited by mirror bandwidths. Solid line is quadratic fit to data

In summary, we have demonstrated a CW diode-pumped DRO with PPLN. The high gain and engineerable phasematching properties of PPLN allow tailoring of the material to match commercially available diode lasers. By holding the piezo at a resonant point of the OPO, the output could be made to run continuously, indicating the potential for stabilising the OPO power with servo control of the cavity length. The output spectrum was erratic, but with the addition of vibration and environmental isolation, we expect better spectral behaviour. With these improvements, this device has the potential to be a useful CW tunable infrared source. Future work will include nondegenerate operation for broader spectral coverage.

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Partially relaxed multiquantum well InGaAs/AlGaAs heterojunction phototransistor operating at 955–970nm

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Indexing terms: Aluminium gallium arsenide, Gallium indium arsenide, Phototransistors, Semiconductor quantum wells

The authors report a partially relaxed InGaAs multiquantum well based heterojunction phototransistor with high responsivity in the transmission window of the GaAs substrate which shows no degradation in performance due to lattice relaxation. The peak responsivity increased from 10A/W at 0.5μW incident optical power to 100A/W at 50μW, corresponding to a current gain of 925. At 8V collector-emitter voltage the responsivity is constant from 957 to 973nm, with a responsivity of 5A/W at 0.5μW and 55A/W at 50μW.

Vertical integration is of particular interest as it enables dense arrays of optoelectronic elements for applications in parallel optical transmission and processing to be fabricated. By vertically integrating light emitters and modulators with detecting and amplifying devices, switching and logic functions with optical gain for fan-out and loss compensation can be realised [1]. Devices that operate in the transmission window of the GaAs substrate are desirable since they facilitate cascading of arrays.

Our interest lies in heterojunction phototransistors (HPTs) since they provide both light detection and electrical amplification. HPTs operating in the transmission window of the GaAs substrate normally use strained InGaAs absorbers whose thickness is less than the critical thickness t_c, since the onset of lattice relaxation beyond this point is believed to deteriorate device performance. To reduce this problem a multiple quantum well (MQW) absorber may be used, placed within a resonant cavity such that the cavity produces an enhancement of the optical absorption [2]. The reason for the MQW structure is that slightly more absorbing material can be used, in terms of t_c, and that it can be optimally distributed in the cavity. Unfortunately, as a consequence of the resonant cavity effect, small variations in layer thicknesses over the wafer lead to variations in resonance wavelength as well as responsivity R [3]. Furthermore, the optical bandwidth is narrow with a full width at half maximum of <10nm for a device without a top reflector. Allowing the InGaAs absorber to relax to some degree would alleviate this problem, since the absorption length could be increased.

Although relaxation is believed to be detrimental to device performance, few studies have been reported, and those that have do not always fully bear out this assumption. Ramberg *et al.* [4] used a relaxed InGaAs base in heterojunction bipolar transistors without loss of performance, Bender *et al.* showed that the responsivity of *pin* detectors increased linearly with the number of quantum wells (QWs) despite the onset of relaxation [5], and Ghisoni *et al.* saw very little degradation in the optical properties of relaxed *pin* detectors [6]. In this Letter we report on high responsivity heterojunction phototransistors with partially relaxed collector regions with constant responsivity over 15nm.

The epitaxial structure was grown by solid source molecular beam epitaxy with a growth temperature of 580°C except for the intrinsic MQW region where the temperature was reduced to 520°C. The nominal structure consisted of an n^+-GaAs buffer layer ($3 \times 10^{18} cm^{-3}$), followed by a 1μm intrinsic collector, containing twenty 80Å $In_{0.13}Ga_{0.87}As$ QWs with 150Å GaAs barriers, a 1000Å p-GaAs ($5 \times 10^{17} cm^{-3}$) base, a 2000Å n-$Al_{0.3}Ga_{0.7}As$ emitter ($5 \times 10^{17} cm^{-3}$), a 1000Å n^+-$Al_{0.3}Ga_{0.7}As$ layer ($3 \times 10^{18} cm^{-3}$), and a 1000Å n^+-GaAs ($3 \times 10^{18} cm^{-3}$) contact layer. The structure is expected to be partially relaxed, and this is confirmed by a clear cross-hatching pattern seen using Normaski interference microscopy. From earlier experience with relaxed InGaAs/GaAs MQWs we expect the structure to be ~20% relaxed. A nonrelaxed control wafer, identical except that it contains only six QWs, was grown in the same batch for performance comparison. The transistors from this wafer indeed show a responsivity of about one-third that of those from the relaxed wafer, indicating that the relaxation has not detrimentally affected the electrical characteristics of the device. In fact, this indicates that the current gain is about the same in the two structures.